LLNL-JRNL-406128

Electrical Strength of Multilayer Vacuum Insulators

J. R. Harris, M. Kendig, B. Poole, D. M. Sanders, G. J. Caporaso

August 8, 2008

Applied Physics Letters

Disclaimer

Electrical Strength of Multilayer Vacuum Insulators

J.R. Harris[a], M. Kendig, B. Poole, D.M. Sanders, and G.J. Caporaso

Lawrence Livermore National Laboratory, Livermore, CA 94551

ABSTRACT

The electrical strength of vacuum insulators is a key constraint in the design of particle accelerators and pulsed power systems. Vacuum insulating structures assembled from alternating layers of metal and dielectric can result in improved performance compared to conventional insulators, but previous attempts to optimize their design have yielded seemingly inconsistent results. Here, we present two models for the electrical strength of these structures, one assuming failure by vacuum arcing between adjacent metal layers and the other assuming failure by vacuum surface flashover. These models predict scaling laws which are in agreement with the experimental data currently available.

[a] Electronic mail: harris89@llnl.gov

One important constraint on the design of particle accelerators and pulsed power systems is the voltage-holding ability of their vacuum insulators. When subjected to strong electric fields, vacuum insulators generally fail by surface flashover, rather than through the bulk material [1]. It has long been known that the electric field which can be sustained by an insulator scales as $length^{-1/2}$ [2]. This suggests that a structure composed of thin dielectric layers would be able to withstand a higher field than a monolithic insulator of the same length and dielectric material, which is the basis of the "High Gradient Insulator" (HGI) concept. HGIs consist of alternating layers of dielectric and metal, and have been shown to withstand gradients up to four times higher than conventional insulators of similar shape [3].

The absence of good quantitative models describing HGI performance caused previous attempts at optimization to rely heavily on empirical studies. Despite promising results, this work led to widely differing conclusions. Sampayan used 20,000 Å gold layers sputtered on submillimeter silica layers treated with a final polishing operation, and found improved results with thinner dielectric layers, in agreement with the length scaling for conventional insulators [3]. Leopold used assemblies formed from Kovar and alumina, with insulator thickness (I) and metal thickness (M) on the order of 1 mm, with $I+M$ = 4 mm, and with a surface polished to better than 0.1 μm. He found improved performance for $I/M<3$, which prevented the initiation of a secondary electron avalanche spanning multiple layers [4]. HGIs assembled from submillimeter sheets of dielectric and metal have been tested by Elizondo [5], Cravey [6], and us [7,8]. These samples had metal layers which were nominally flush with the surface or protruding into the vacuum, and generally showed improved performance as I/M increased.

These structures were all intended to interrupt the secondary electron avalanche widely believed to initiate surface flashover [9]. However, our recent results [7,8] led us to reconsider the failure mechanism of HGIs. Samples tested in our experiments were machined from sheets of Rexolite and stainless steel laminations. Surface measurements showed that the metal layers protruded beyond the dielectric layers by 10 μm, likely due to thermal expansion of the Rexolite during machining. Although simulations indicated that this protrusion would not significantly alter electron trajectories near the surface, it did provide a direct line of sight between adjacent metal layers. HGIs examined before testing showed ragged microprotrusions on the metal layers, also believed to be an artifact of the machining process (Fig. 1). Discharge events during high-voltage testing consisted of many small discharges between adjacent metal layers, often widely scattered over the HGI surface. And at locations where discharges were particularly prominent, the metal layers were eroded, with a surface structure suggesting the melting and rapid refreezing of the metal, and white material was deposited in streaks consistent with the shape of the discharges. Energy-dispersive x-ray measurements detected chromium in these streaks, confirming that they were formed by the ablation and redeposition of the stainless steel layers.

These results suggested that the insulators might be failing by vacuum arcing between adjacent metal layers, rather than surface flashover of the dielectric layers. For small vacuum gaps and relatively high fields, the electric field E_{BD} needed to initiate a vacuum arc is generally found to be independent of vacuum gap length [10]. Consider an

HGI made of alternating layers of metal and dielectric, where each period is identical and there is no interlayer coupling. The voltage held across each dielectric layer will be $E_{BD}I$, and the voltage held by a stack with N periods will be $E_{BD}IN$. The structure length L_S is related to the number of periods by $L_S = N(I+M)$, so the average electric field held by the HGI is

$$E_{HGI} = \frac{E_{BD}}{1+\left(\frac{I}{M}\right)^{-1}} . \tag{1}$$

This formula is in good agreement with our results (Fig. 2) and those of Elizondo (Fig. 3), and agrees qualitatively with those of Cravey. Because E_{BD} was not measured in these experiments, we treat it as a fitting constant. Values of E_{BD} inferred from these experiments are less than the enhanced, microscopic threshold field for stainless steel by a factor of approximately 300, an enhancement factor consistent with those reported in the literature [11].

In each of these experiments, structure performance was generally seen to increase with I/M, as predicted by Eq. (1). This differs from the scaling seen by Sampayan and Leopold, whose HGI configurations avoided a direct line of sight between metal layers. If we repeat the derivation of Eq. (1), but assume the $I^{-1/2}$ scaling for surface flashover, the HGI strength becomes

$$E_{HGI} = E_M \sqrt{L_S}\,\frac{\sqrt{I}}{I+M} , \tag{2}$$

where the dielectric material has a breakdown field E_M when tested with a sample of length L_S. In the Leopold experiments, $I+M$ was held constant, E_M = 5.1 MV/m, and

L_S = 16 mm. The HGI electrical strength calculated from Eq. (2) agrees to within 15% of Leopold's experimental results for HGI configurations with $I/M < 3$ (Fig. 4). Note that when Leopold tested a sample with I = 0.97 mm and M = 3.03 mm, he found that the HGI held 5.1 MV/m, identical to the strength of a monolithic insulator of the same size and using the same dielectric material. This is explained by Eq. (2), which predicts $E_{HGI} = E_M$ when $\sqrt{L_S I} = I + M$. For $I/M > 3$, Leopold has shown the existence of a secondary electron avalanche spanning multiple periods, which establishes interlayer coupling and violates an assumption used to derive Eq. (2).

Equations (1) and (2) predict that when both failure modes are allowed, surface flashover will dominate for thicker dielectric layers and vacuum arcing will dominate for thinner dielectric layers. For a given I/M, the HGI electrical strength will initially increase as I is made smaller until the transition to failure by vacuum arc occurs, after which it will remain constant. This transition is determined by

$$I_t = \left(\frac{E_M}{E_{BD}} \right)^2 L_S . \qquad (3)$$

The model described in this letter can be summarized as follows. When HGIs have metal layers protruding into the vacuum, both surface flashover and vacuum arcing are potential failure mechanisms. The surface flashover strength associated with a dielectric layer increases as its thickness is made smaller while its vacuum arc strength remains constant, so that flashover will dominate for large thicknesses and vacuum arcing will dominate for small thicknesses. In each regime, the electrical strength of the HGI can be calculated by simple equations which rely on measurable material parameters and on known scaling laws for the two discharge types. These models only hold in the absence of interlayer coupling, but are otherwise in good agreement with the experimental data currently available. When vacuum arcing is a potential failure mechanism, it establishes the upper limit on HGI electrical strength that can be achieved with given materials. Improved designs should seek to avoid the possibility of vacuum arcing [12], allowing performance to be further improved by use of thinner dielectric layers.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

References

[1] H. Craig Miller, IEEE Transactions on Electrical Insulation **24** 765-785 (1989).

[2] A.S. Pillai and R. Hackam, Journal of Applied Physics **58** 146-153 (1985).

[3] S.E. Sampayan, P.A. Vitello, M.L. Krogh, and J.M. Elizondo, IEEE Transactions on Dielectrics and Electrical Insulation **7** 334-339 (2000).

[4] J.G. Leopold, U. Dai, Y. Finkelstein, E. Weissman, and S. Humphries, IEEE Transactions on Dielectrics and Electrical Insulation **12** 530 (2005).

[5] J.M. Elizondo, *Microstack Insulator for Flashover Inhibition: Phase II*, Defense Nuclear Agency Technical Report DNA-TR-91-86 (1992).

[6] W.R. Cravey, G.L. Devlin, C.S. Mayberry, and J.N. Downing, in Proceedings of the 1997 Pulsed Power Conference, pp. 555-558 (1997).

[7] J.R. Harris, R.M. Anaya, D. Blackfield, Y.-J. Chen, S. Falabella, S. Hawkins, C. Holmes, A.C. Paul, S. Sampayan, D.M. Sanders, J.A. Watson, G.J. Caporaso, and M. Krogh, IEEE Transaction on Dielectrics and Electrical Insulation **14** 767-802 (2006).

[8] J.R. Harris, D. Blackfield, G.J. Caporaso, Y.-J. Chen, S. Hawkins, M. Kendig, B. Poole, D.M. Sanders, M. Krogh, and J.E. Managan, Journal of Applied Physics **104**, 023301 (2008).

[9] R.A. Anderson, Applied Physics Letters **24** 54 (1974).

[10] G.A. Mesyats and D.I. Proskurovsky, *Pulsed Electrical Discharge in Vacuum*, Springer-Verlag: Berlin (1989), Section 2.2.3.

[11] P. Kranjec and L. Ruby, Journal of Vacuum Science and Technology **4** 94-96 (1967).

[12] Patents pending.

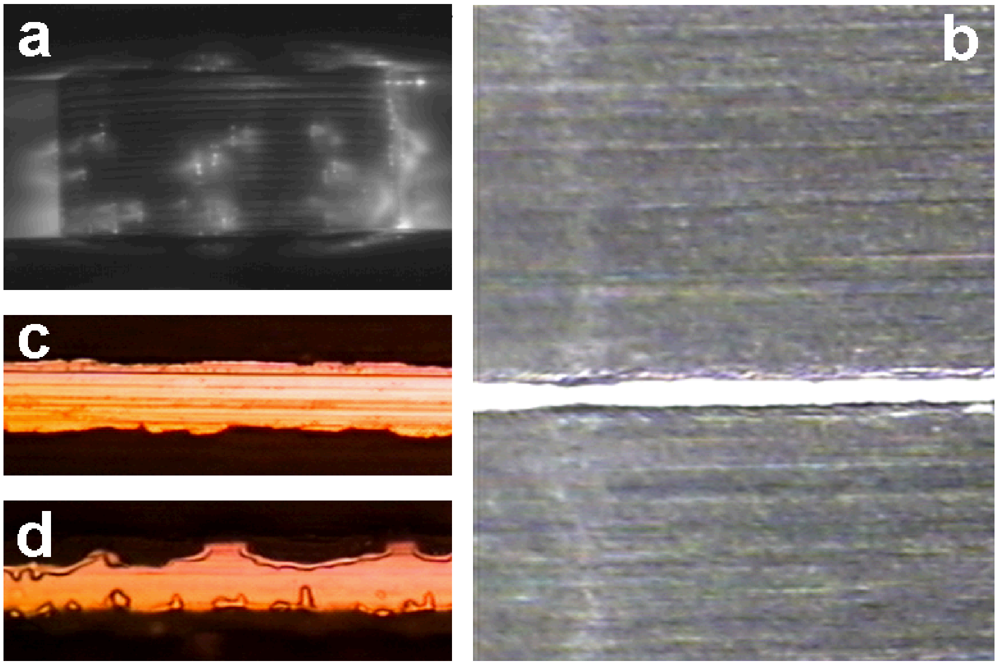

Figure 1. (Color online) HGI discharge and damage: a) typical discharge event, b) vertical white streak containing chromium and region of ablation, c) typical stainless steel layer before testing, and d) typical stainless steel layer after testing.

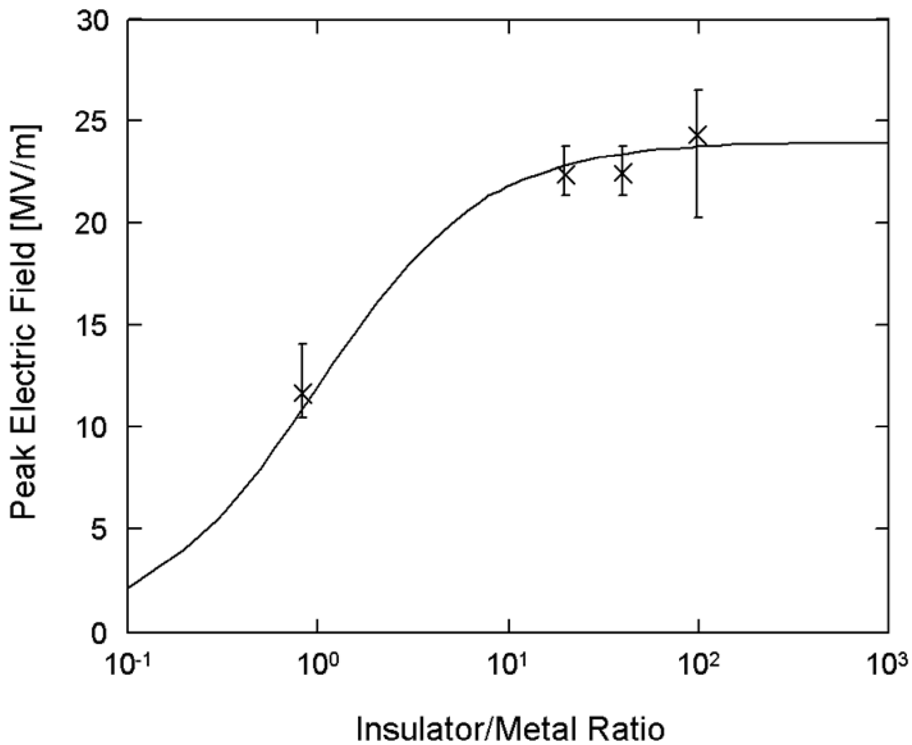

Figure 2. Results from testing of Rexolite and stainless steel HGIs, as described in Ref. [8], compared to Eq. (1) with E_{BD} = 24 MV/m. A single data point at $I/M = 40$ was rejected because that sample was damaged prior to testing.

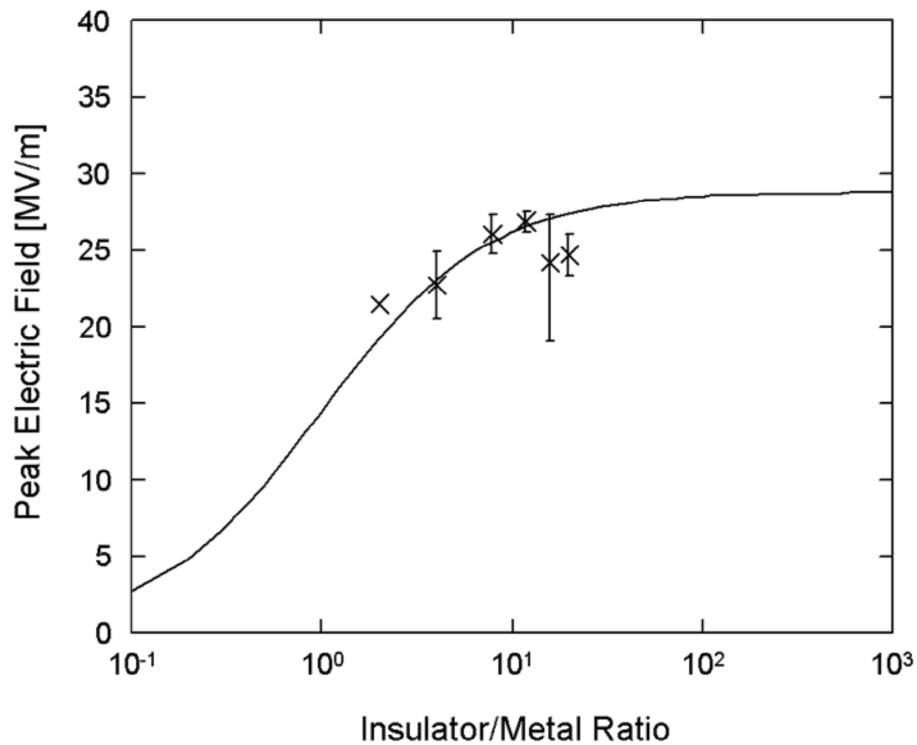

Figure 3. Elizondo's data for Mylar and stainless steel HGIs with metal layers protruding by 40 mil, from Ref. [5], compared to Eq. (1) with E_{BD} = 28.7 MV/m.

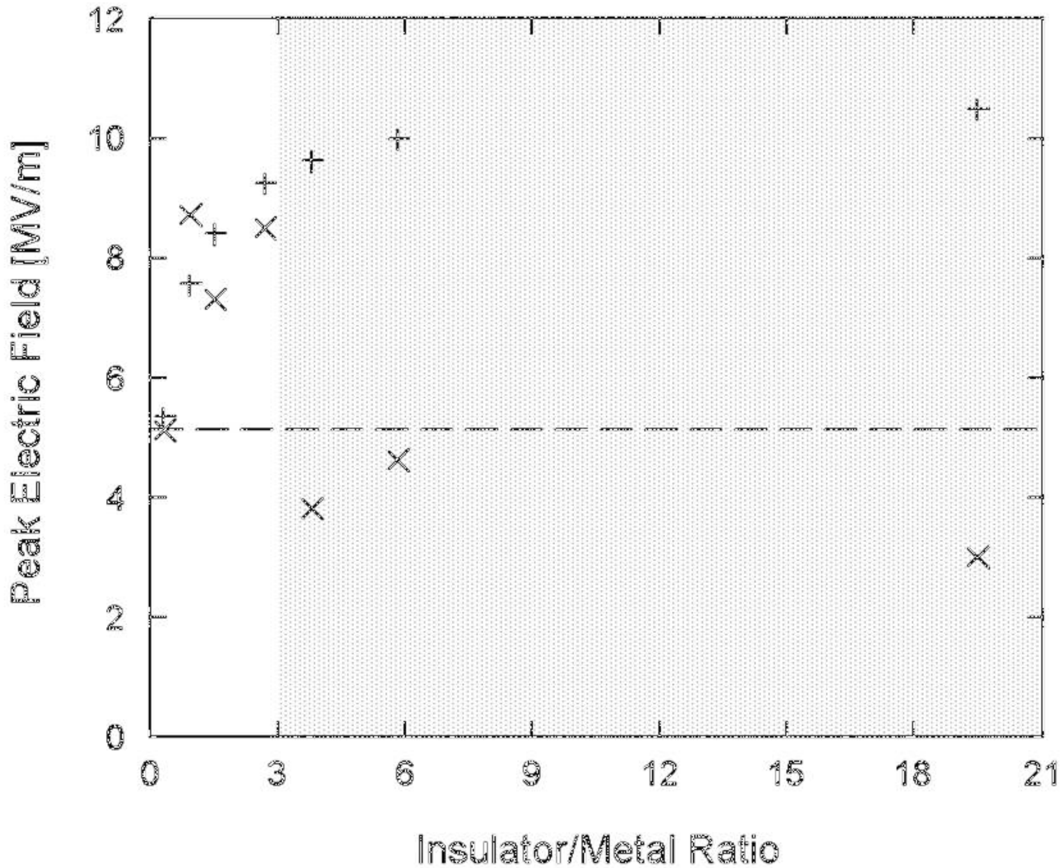

Figure 4. Leopold's data [4] for Kovar and alumina HGIs (x), plotted against Eq. (2) with E_M = 5.1 MV/m, L_S = 16 mm, and $I + M$ = 4 mm (+). The dashed line represents the strength of the conventional insulator (E_M). Shading represents the region of interlayer coupling, which violates an assumption used to derive Eq. (2). Note the good agreement when there is no interlayer coupling.